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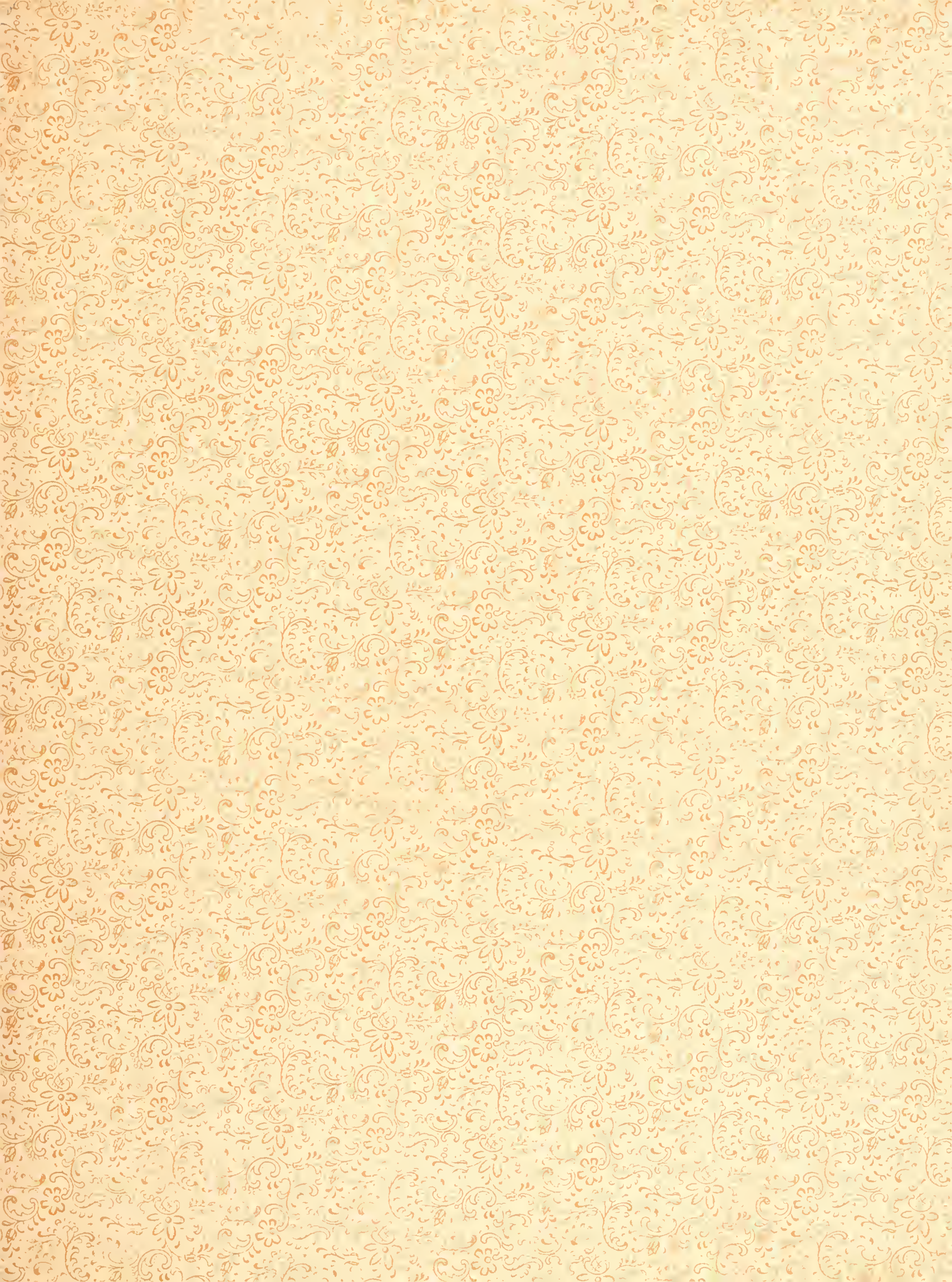

THE EFFECT OF FREQUENCY UPON THE CORONA.

A DISSERTATION
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By

WILLIAM STUART GORTON.

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FOREWORD.

The corona is the name applied to the phenomena, viz. ionization, light, and sound, which take place in the neighborhood of an electrically charged conductor when its potential is raised above a certain amount. In investigating the corona both alternating and direct potentials have been employed, principally the former. In the present work alternating potentials alone have been used.

INTRODUCTION.

In a paper by Whitehead[*], it was shown that, within the range of frequency from 20 to 90 cycles per second, the frequency had a measurable effect on the voltage (maximum of the wave) at which the corona began. For a detailed account of the method used reference must be made to the original paper, but the principle of the method is simple and will be described briefly here. The corona was formed about a wire which was stretched coaxially in a metal cylinder, the ends of the cylinder being closed by insulating bushings. Air could be led into the cylinder by a lateral tube near one end and out by a lateral tube near the other end. Immediately after leaving the cylinder the air passed over an insulated electrode which was connected to a gold-leaf electroscope. The walls of the cylinder where the lateral tubes were connected were drilled with numerous small holes. The air could thus pass freely and at the same time the electrode could not be influenced electrostatically by the presence of the highly

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[*] Whitehead, Trans. A.I.E.E. vol XXX, part 3, p. 1857, 1911.

[†] Whitehead, Trans. A.I.E.E. vol XXIX, part 2, p. 1159, 1910.

charged wire at the axis of the cylinder. The cylinder was always earthed.

The value of the voltage delivered by the high tension side of the transformer was determined from a knowledge of the ratio of transformation and from oscillograms taken of the voltage impressed across the low tension terminals of the transformer. It was assumed as usual that the wave shape of the high tension e.m.f. was the same as that of the low tension e.m.f.

As the voltage applied to the wire is gradually raised a point comes when the air around the wire is ionized, that is, becomes conducting. The electroscope, as soon as this occurs, begins to lose its charge. It was found[+] that the point at which the electroscope began to leak was not influenced at all by the velocity of the air through the tube, although the rate of leak was affected by the velocity. In the earlier one of the papers before referred to, it was shown that ionization and the visual corona were entirely contemporaneous. It was shown, too, that for a given size wire and tube under ~~one~~ the same conditions of temperature and pressure, the corona always began when the voltage in its cycle reached a fairly definite ~~volume~~ value and that this ~~volume~~ value was approximately the same as the maximum value of the voltage wave for the point where the electroscope first began to leak. Another result was

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[+] Reference at bottom of p. 1.

that the electric field strength at the surface of the wire when corona began was independent of the size of the tube. Judging from the above results concerning the appearance of the corona at a definite point in the cycle, it might have been expected that the corona voltage would be independent of frequency. This turned out not to be the case. The corona voltage was found to decrease with increasing frequency. A curve plotted between frequency and the maximum value of the voltege wave for the critical voltage (i.e.beginning of corona) showed a fairly regular decrease from 20 cycles to 90 cycles. This decrease had the same percentage value for the various sizes of wire tried. The voltage at 90 cycles was about 6 per cent lower than the voltage at 20 cycles.

The influence of frequency has been investigated by several other workers in this field. Peek[*], in the range of frequency from 40 to 100 cycles per second, was unable to detect any influence of frequency either on the voltage at which the visual corona started or on the voltage at which the loss began. Weidig and Jaensch[†] have investigated the instantaneous values of the voltage at which the visual ~~voltage~~ Corona starts on the voltage wave. Their results on this point may be summarised as follows :

Effective Voltage (K.V.)	Corona begins (K.V.)	Corona ends (K.V.)	
32.0	45.0	45.0	
40.0	37.0	54.0	Frequency
60.0	27.5	76.0	50 ~
80.0	17.0	88.0	
100.0	9.0	108.0	

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[*] Peek,Trans.A.I.E.E.vol 31,part 1,p.1055,1912.

[†] Weidig and Jaensch,Electrotechnische Zeitschrift,Heft 23&24,1913.

These results are in striking disagreement with those found by Whitehead. Very recently Alexanderson* has found that at 100,000 cycles per second between a 3-inch spark gap spheres 5 inches in diamater breaks down at approximately the same voltage (100,000 volts) that it does at commercial frequencies ; a 5-inch gap between plane parallel plates, however, was found to break down at 30,000 volts - a much lower value than the break down voltage for commercial frequencies.

PRELIMINARY INVESTIGATION.

The work reported here was undertaken in order to extend the observations of the corona voltage over a wider range of frequency than that mentioned above in the work of Whitehead. The generator available was a small one driven by a direct-connected two-horsepower motor. This generator, although structurally a unit, consisted in fact of two generators ; one having 48 poles and the other 240 poles. The rated speed was 1500 revolutions per minute. Consequently at the rated speed one generator gave 600 cycles and the other 3000 cycles per second. Each machine was rated at 110 volts, 5 amperes. The transformer first used was rated at 500 watts, 100-10,000 volts at 133 cycles per second.

The second transformer used - it was employed in the larger part of the work - was rated at 3000 watts at 60 cycles ; the low tension winding was in two sections,

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*Alexanderson, General Electric Review, p. 427, April 1914.

the rated voltage per section being 50 volts; the high tension winding was in four sections, the rated voltage per section being 6250 volts.

The motor driving the high frequency generator was connected to the direct-current city mains (240 volts). The field of the generator was supplied from a 120-volt storage battery. The conditions were thus favorable to steadiness in the readings. The large moment of inertia possessed by the revolving field of the generator prevented any sudden changes in speed due to changing voltage of the direct current supply. The speed of the generator was controlled partly by the use of resistance in the motor armature circuit and partly by varying the resistance of the motor field circuit.

Speeds from normal to three-quarters normal were obtained by the use of armature resistance ; speeds from three-quarters to half normal were obtained by running the motor armature from the 120 volt mains and by the use of resistance in the field circuit. It was not feasible to run the machine at any speed much below half speed, partly because of the large field current required by the generator, and partly because the speed was more liable to fluctuations.

The plan of work adopted involved varying the speed

of the generator so as to include the whole range of possible frequencies within a period of two or at most three hours. This meant large variations in the field current of the generator in order to obtain the proper voltages. The generator, moreover, had a very large armature reaction ; the terminal voltage was consequently very sensitive to changes in the armature current. Under these conditions the control of the voltage delivered to the high tension transformer by means of an autotransformer was considered to offer no advantages. Consequently, control of the voltage was effected solely by varying the field current of the generator.

The corona apparatus proper consisted,as in previous experiments, of a wire stretched coaxially in a metal tube. At a point equidistant from the ends of the tube were drilled numerous small holes (about 1/8 inch in diamater). The electrode,which consisted of a brass disc having the same curvature as the tube, was placed over these holes and as near the tube as could conveniently be done without having metallic contact. A grounded metallic shield was placed around the electrode and the connection to the electroscope made through a hole in the shield,the wire being insulated from the shield by means of a plug of sulphur. The electroscope was a very sensitive one ; it gave a workable deflection of the gold-leaf when charged to a potential of 120 volts. As it had been shown in the previous experiments of Whitehead that the break down voltage of air was independent

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of the velocity of the air through the tube, no provisions were made for circulating air in the tube. In the earlier part of the work the ends of the tube were left open, the wire being stretched between insulating supports situated at some distance beyond the ends of the tube. In the latter part of the work the ends of the tube were closed by insulating caps,the wire passing through holes in the caps. Fig.1 represents the general plan of the tube.

Observations were first made on a brass wire 0.089 cm.(0.0350 in.) in diamater in a tube having an internal diamater of 4.9 cm. The 500 watt transformer mentioned above was used. The procedure was to raise the voltage applied to the transformer by increasing the field current of the generator until the electroscope began to discharge. The field current was then decreased until the leak of the electroscope stopped, and then increased again. The voltage at the instant the leak began was read by a hot-wire voltmeter connected across the low-tension terminals of the transformer. The speed was read by a carefully calibrated tachometer.No oscillograph was.available at the time these preliminary measurements were made, consequently no account could be taken of any change in wave shape ; indeed at the highest frequency attained,namely 3000 cycles per second, the

oscillograph is unreliable. In the neighborhood of 600 cycles, the electroscope began to leak at about 80 volts, at 1400 cycles at 73 volts, and finally at 2800 cycles at 37 volts; the decrease in voltage from 1400 to 2800 cycles was fairly regular. From what is known of the mechanism of the corona it seemed highly improbable that the corona voltage actually experienced as great a change as was indicated by the above figures, so to test the matter a high tension electrostatic voltmeter was attached to the terminals of the transformer.

It was found that the corona voltage as indicated by the static voltmeter remained constant. The corona tube was then disconnected and the voltage adjusted so that this voltmeter read 10 kilovolts. At 60 cycles the low tension voltage was 82.5 volts, and at 2750 cycles 31 volts. It was thus seen that the ratio of transformation of this transformer is over two and one-half times as great at 2750 cycles as it is at 60 cycles. The cause of this great change is to be sought in the capacity of the high-tension windings. The charging current taken by the high tension windings, other things being equal, is directly proportional to the frequency. The reactance of these same windings is also directly proportional to the frequency. Consequently one would expect the disturbing effect of the charging current on the ratio of transformation to be, roughly, directly proportional to the square of the frequency. That the current taken by the transformer was actually leading was

easily shown. An electrodynamometer had been inserted in the low tension side to measure the current, which was incidentally about 5.5 amperes,- ten times the value of the current taken at 60 cycles for the same high tension voltage. The large reactance of the instrument (22 ohms at 2750 cycles) was in one way a disadvantage because the voltage drop across it was so great, but in another way it was a very great advantage because by applying the three voltmeter method to the dynamometer and transformer the relative power factor of the two could be at once determined. The power factor of the dynamometer was determined by putting it in series with incandescent lamps (assumed non-inductive) and applying the same method. It was found that the current taken by the transformer at 2750 cycles was leading the voltage by about 60 degrees.

Some experiments were next performed upon the 3000 watt transformer. The high tension voltage was not measured but the effect of different methods of connection of the high-tension coils was studied. All the experiments were conducted at about 2750 cycles. A few examples of the results may prove of interest. With all the high-tension windings in series and one end of the winding connected to ground, the transformer took 3.1 amperes at 3.5 volts, the current leading the voltage by about 20 degrees; the high-tension windings were entirely disconnected from all other apparatus. With the high tension windings connected two in

series, two in parallel, the same point being earthed as formerly, the transformer took 4.0 amperes at 33.5 volts, the current leading the voltage by about 90 degrees. In both cases the low tension windings were in series. These two cases are fair samples of the results found in the course of the experiments and indicate that the method of connecting the high tension windings has a very profound effect on the conduct of the transformer. There was also evidence that at one frequency within the range used the transformer was in resonance. With a certain arrangement of the high tension windings and running at 2750 cycles the switch of the driving motor was opened. The speed began at once to decrease but the voltage applied to the transformer and the current taken by it both began to increase and kept on increasing until it was necessary to open the transformer circuit in order not to injure the instruments. There were also indications that by far the larger part of these capacity effects was due to the capacity between winding and core and not between different parts of the winding, for it was found that conditions on the low tension side of the transformer depended only upon the maximum voltage (from ground) reached in the high tension winding ; thus the effect produced by connecting all the coils in series and grounding the middle point of the winding

was the same as that produced by connecting the windings two in series and two in parallel and grounding one end.

It is very probable that the 6 per cent lowering of the corona voltage in going from 20 to 100 cycles observed by Whitehead was due entirely to the capacity effects in the transformer used ; all measurements were made on the low tension side.

METHOD FOR MEASURING MAXIMUM VOLTAGE.

It was at once evident from the results of the tests described above that any measurements of corona voltage in order to have any validity whatever, would have to be made on the high tension side of the transformer, and not on the low tension side. This condition coupled with the unreliability of the oscillograph for the higher frequencies made it impossible to obtain a complete knowledge of the wave shape except by the use of the cathode ray oscillograph; consequently a partial knowledge of the wave shape had to suffice. The previous work of Whitehead indicated that the corona began when the maximum voltage of the wave reached a certain definite value ; the theory of ionization by collision would also indicate this. Consequently a knowledge of the maximum value of the voltage reached in the cycle seemed of greatest importance. The only method available for finding the maximum was the one first used, to the author's knowledge, by Chubb and Fortescue*. The method consists essentially of applying the voltage to be investigated

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*Chubb and Fortescue, Proc. A.I.E.E. p. 627, Feb. 1913.

to a condenser and measuring the average value of the current taken by the condenser. Let V represent the maximum value attained by the voltage, C the capacity of the condenser and f the frequency. The time taken by the voltage in passing from its maximum value in one direction to its maximum in the other is $\frac{1}{2f}$. In this time the current goes from zero to a maximum and back to zero again. Its average value is equal to the total charge which has passed through the circuit divided by the time taken for the charge to pass. In symbols :

$$i_{av.} = \frac{1}{\frac{1}{2f}} \int_0^{\frac{1}{2f}} i\,dt = \frac{2VC}{\frac{1}{2f}} = 4fVC.$$

$$\therefore \quad V = \frac{i_{av.}}{4fC}. \qquad (1)$$

In order to measure the average value of the charging current taken by the condenser it is necessary to employ a measuring instrument of the permanent magnet type and to rectify the current before it passes into the instrument or, what amounts to the same thing, to allow only one-half of the current wave to pass through the instrument; in this latter case the reading of the instrument must be multiplied by 2 in order to get the average value of the current. Chubb and Fortescue made use of a mechanical device in order to have only one half of the current wave pass through the measuring instrument. In the present work the use of a

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mechanical device was out of the question on account of the high frequencies employed. In search of a non-mechanical rectifying device one naturally turns to the mercury arc. The rectifying properties of this arc when playing between a mercury and an iron electrode are well known.

The arc permits current to flow from the iron electrode to the mercury one with only a trifling drop of voltage in the arc ; no current can flow in the opposite direction until the applied voltage has risen so high as to cause a vacuum discharge to pass through whatever gas may be present. The mercury arc, moreover, is a very quick-acting affair. It has been shown that the arc will be extinguished if the current supply is interrupted for as much as the ten-millionth part of a second. Thus, the conductivity due to the passage of the current dies out with enormous rapidity. In the present case the current taken by the condenser could not be used itself to maintain the arc, in the first place on account of its small value and secondly because of the peculiar requirements of the experiment. As a consequence the cathode had to be kept active by an arc (maintained by a direct current) playing between the cathode and an auxiliary mercury anode.

The form of tube which was adopted after considerable experimenting is illustrated in Fig.2. The tubes were made from German soft glass tubing having approximately an internal diameter of 1.0 cm and walls 1 mm.thick. The iron electrode con-

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sisted of about 6 cm. of No. 30 iron wire which had been well oxidised by passing through the flame of a blast lamp. The object sought in making the iron electrode so small was to prevent mercury from condensing on it to any extent. In a previous form of tube the iron electrode was much larger with the result that mercury condensed on the electrode and dropped off. This last action interfered seriously with the proper functioning of the tube as every time a drop fell off an arc would be started irrespective of the direction of the voltage acting across the gap. A small wire attains the temperature of the surrounding mercury vapor much more nearly than a more massive electrode does ; consequently condensation is much reduced. The object sought in oxidising the electrode was to prevent the amalgamation of the iron and the condensed mercury which occurs if the iron is not oxidised. The presence of such an amalgamated surface seems to facilitate condensation enormously. The tubes were exhausted while running until the pressure of the residual gas was less than 0.0001 mm.

A diagram of the connections of the apparatus is shown in Fig.3. It will be seen from it that during one half of the wave the charging current of the condenser passes through one of the two tubes used and during the other half through the other tube. A Weston direct current voltmeter was used as a current measuring instrument. This voltmeter was in circuit with one of the tubes ; consequently in order to get the average value of the current its reading had to be multiplied by 2. The voltmeter

gave full scale deflection for a current of approximately 0.01 ampere. The 1.5 volt scale (resistance approximately 156 ohms) of the instrument was used ; it seemed to make no difference, however, even when the 150-volt scale was used instead. The instrument gave the same reading no matter with which tube it was in circuit ; the reading was also unaffected by the presence of a similar instrument in series with the other tube. These last two results are of great importance. The former shows that the two tubes used functioned in precisely the same way ; the latter shows that the presence of the current-measuring instruments had no effect upon the process of rectification. Each tube, moreover, was carefully tested to see whether the degree of rectification was as complete as was desired. When the arc was playing between the two mercury electrodes a 240 volt difference of potential was applied between the mercury cathode and the iron electrode, suitable resistances being in the circuit for protection. When the iron electrode was positive with respect to the mercury cathode a current promptly flowed and the drop of potential across the tube was about 50 volts, independent of the amount of current flowing. When the iron electrode was negative with respect to the mercury cathode, no current that could be detected by a Weston voltmeter flowed. The use of a sensitive galvanometer showed that the current flowing was not greater than the five-millionth part of an ampere. As the tubes were used to rectify currents of the order of magnitude of 0.01 ampere the rectification was thus practically perfect. Finally the tubes

were set up in series with a condenser as shown in Fig. 3 and tested at various frequencies from 45 to 75 cycles. The assumption was made that in this range of frequencies the ratio of transformation remained constant and that the wave shape of the high tension e.m.f. was the same as that of the low tension e.m.f. The results obtained were in accord with what the theory of the experiment would indicate to within the probable error of the measurements.

METHOD FOR MEASURING EFFECTIVE VOLTAGE.

While a knowledge of the maximum value of the voltage wave seemed, of course, of greatest importance, still it was considered desirable to find out about the wave shapes used as much as could conveni~~tme~~ently be done. About the only other quantity connected with an alternating voltage that can be ascertained with any degree of ease is the effective value. In this case a knowledge of the effective value of the voltage is particularly desirable because of the knowledge it gives concerning the ratio of transformation and the wave shape. Having the values of the maximum and of the effective voltages does not tell one very much about the wave shape but it at least enables him to say roughly whether the wave is or is not a sine wave, and if it is not whether it is flat-topped or peaked. Concerning minor irregularities on the wave nothing, of course, can be said.

An electrostatic voltmeter seemed to be the most suitable means of finding the effective values of the high

tension voltage. It was desired to have an instrument which would give the effective value of the voltage to 1/2 of one per cent or better and which at the same time would be fairly quick-reading. These requirements pointed to a Crémieu electrostatic-electrodynamic balance, as the proper instrument. The principle of this instrument is as follows : The voltage to be measured is applied to two discs one of which is mounted at the end of one arm of a balance beam. The attraction between these discs is balanced by the repulsion exerted between two coils, one of which is fixed at the other end of the balance beam; a constant direct current from some suitable source is passed through these two coils which are in series. This current is adjusted until the balance is in equilibrium in the same position that it occupies when no electric or magnetic forces are acting. When this is the case the moment exerted around the knife edge by the electric forces is equal and opposite to the moment of the magnetic forces. Now the moment of the electric forces varies directly as the square of the voltage between the discs and the moment of the magnetic forces varies directly as the square of the current flowing in the coils. Consequently when the balance is brought into the proper position of equilibrium the voltage between the discs is directly proportional to the current flowing in the coils. If, as in the present case, the voltage is alternating, the moment is proportional to the average

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square of the voltage which is by definition the square of the effective value. Hence the effective value of the voltage is directly proportional to the current flowing in the coils.

The author~~s~~ was fortunate in having available a balance beam with a very fine knife-edge of agate mounted in a large glass case. All magnetic material had been carefully excluded from the construction of the balance and case. This balance beam was fitted with a disc and coil as shown in Fig.4. The discs were of aluminum and were 10 cm. in diameter. The distance between the fixed disc and the moving disc (which was of course rigidly connected to the balance beam) was 3.2 cm. The moving coil (also rigidly connected to balance beam) consisted of 50 turns of No.18 copper wire. The fixed coil had 1200 turns, also of No.18 wire. The current was led into the moving balance system by means of two silver strips each 0.0013 cm. (0.0005 in.) thick, 1 mm. wide and 6 cm. long. The points of support of a strip were only 4 cm. apart so that the strip had a very considerable sag. These silver strips would carry about 3.5 amperes before burning out. The largest current they were ever called on to carry was about 1 ampere ; with this value of the current the heating of the strips was never enough to cause any disturbance of the balance due to air currents. The strips also seemed to have no effect on the sensibility of the balance or on the stability of the zero point. In using the

balance current for the coils was taken from a storage battery. When the voltage applied to the discs was steady,-a condition, unfortunately,not often fulfilled - readings could be repeated to within 1/5 of one per cent. When the voltage was unsteady differences of one per cent frequently occurred in the readings.

CORONA OBSERVATIONS

EXPERIMENTAL DETAILS.

The problem of investigating the corona over the range of frequency from 60 to 3000 cycles is a very large one and in the present work it was decided to investigate only the effect of frequency all other conditions being kept as nearly constant as possible. The effects of pressure and temperature upon the corona have not been investigated at any frequency much above 60 cycles. Consequently we cannot say that the effects of temperature and pressure at 3000 cycles are the same as at 60 cycles, even although the theory of ionization by collision would lead one to expect that they are the same.Therefore in order to find out the effect of frequency alone it was necessary to make observations over the whole range of frequency in such a period of time that the pressure and temperature would remain reasonably constant. Three hours was adopted as the length of such a period. This procedure made rather small the number of different frequencies at which it was possible to make observations but the number of points obtained was sufficient to give a good knowledge of the variation with frequency. Now there is no reason to suppose that the effective

value of the voltage has any particular influence on the corona, consequently it was decided to measure only the *maximum* of the voltage wave when making observations on the corona. The investigation of the effective values of the voltages used was relegated to the end of the work, thus facilitating the work enormously as the effective values of all the different voltages used over the whole range of frequencies could easily be determined in a day, A diagram of the apparatus used has already been given in Fig.3. The voltage on the low tension side of the transformer was read by a Hartmann and Braun hot-wire voltmeter the series resistance of which was wound with specially fine wire to avoid any change in resistance with frequency. The generator and transformer (3000 watts) used have already been described. The speed of the generator was read by a carefully calibrated tachometer; this instrument was a very good one; its accuracy never being less than 1/2 of one per cent and in the most open part of the scale reaching 1/10 of one per cent. The condensers used were of the Moscicki type ; the dielectric was glass and the condensers were filled with oil to avoid corona at the edges of the metallic coatings. Each condenser had a capacity of about 0.002 micro-farad. Now the range of frequency used was from 60 to 3000 cycles- a 50-fold increase. A glance at equation (1) will show that if $\underline{V}$ stays approximately constant over this range (as it actually does) $\underline{i_{av.}}$ will be proportional to the frequency for constant capacity. This state of affairs would mean an enormous variation of the accuracy with the frequency. In order to avoid such

a condition the capacity must be varied with the frequency in such a way as to keep the needle of the current measuring instrument in a suitable part of the scale. This was done by using one condenser at 60 cycles, seven condensers in series for the range from 300 to 600 cycles, and all sixteen condensers in series for the range from 1500 to 3000 cycles. Even with the capacity reduced as much as possible by this means it was impossible with the larger sizes of wires to go much beyond 1500 cycles because the rectified current became larger than could be measured by the instrument employed (a Weston voltmeter); the use of a shunted instrument was, of course,out of the question.

The corona voltage at 60 cycles has already been well determined ; consequently it was sufficient in the present work to find out how the corona voltage varied with frequency. To this end only the relative values of the capacities of the condensers have to be known. These were determined in the following manner : A special generator driven from the city mains by a direct current motor and excited by a storage battery furnished alternating current at about 45 cycles. The low tension voltage was measured by a Weston electrodynamometer type voltmeter. The frequency was measured by a Hartmann and Braun vibrating reed frequency meter. Condenser No.1 was put in position and the low tension voltage,frequency and rectified current read.From seven to nine observations were made on each condenser.Then keeping the frequency,excitation,and all other conditions the same, No.1 condenser was disconnected and No.2 connected in its

place. The observations were made and No.3 was connected and so on for all sixteen condensers. Since the condensers were of approximately the same capacity and conditions were kept constant so carefully, the maximum value of the high tension voltage was directly proportional to the effective value of the low tension voltage, and consequently the value of low tension voltage could be substituted for V in the formula:

$$C = \frac{i_{av.}}{4 f V}$$

in order to find the comparative values of the capacities. The capacity of condenser No.1 was called unity. The capacity of the condensers when connected in series could be calculated by the usual formula. The needle of the direct current instrument vibrated with the frequency of the rectified current, the amplitude being about one-half of a division; on this account the accuracy of the reading was only 1/2%. The frequency could be read to 1/2% and the alternating voltage to 0.1%. The accuracy of any one reading was consequently about 0.7%. Since from seven to nine readings were taken the final accuracy attained was about 0.3%. Repeated measurements on one condenser showed that this was actually the order of accuracy attained.

Two sizes of corona tubes were used in the course of the experiments, one having a diameter of 4.58 cm. and the other a diameter of 6.35 cm. The diameters of the wires used were as follows : 0.317 cm.(0.1249 in.), 0.234 cm.(0.0924 in.), 0.194 cm.(0.0763 in.), 0.164 cm.(0.0644 in.), 0.106 cm.(0.0418 in), 0.089 cm.(0.0350 in.). All of these sizes were of brass except

the one 0.194 cm.in diameter which was of tool steel. The smaller sizes were made straight by heating with an electric current while under tension. The larger sizes were rods which needed no such treatment. Each time before being used the wire was polished with the very finest emery paper until the latter became glazed with brass. A final polish was given with tissue paper. This treatment produced a very good polish. In the earlier part of the work the tube was left open at the ends; for the most part,however, the ends were closed with insulating caps. No difference between the two cases could be detected.

The method of making observations has already been described. The field current of the generator is increased until the electroscope begins to leak, when the rectified current, speed (or frequency), and low tension voltage are read. The last quantity was not essential but was considered convenient to have. The rectified current could be read to 0.1 per cent at frequencies of 300 and more, the needle being without any vibration whatever. The speed could be read always to 1/2 per cent and most of the time better than that. The capacity of the condensers had been determined to 0.3 per cent. Consequently any one observation of the maximum voltage at 300 cycles and over was accurate to 0.6 per cent. At 60 cycles the rectified current could be read to 1/2 per cent, the frequency (the generator was not readily accessible) to 1/2 per cent, and the capacity,as before, was determined to 0.3 per cent. The accuracy was consequently 0.8 per cent. In practice the most convenient units of

current and capacity were as follows : of current, the current required to deflect the Weston direct current voltmeter one scale division, of capacity, the capacity of condenser No.1. The formula for the maximum voltage then becomes:

$$V = k\,\frac{V_{d.c}}{fC} \qquad (2)$$

where k is a suitable constant. There is just one more point about the use of these condensers that needs discussion, and that is the connection between the capacity of the condensers and frequency. The Bureau of Standards is authority for the statement that the capacity of Mościcki condensers does not vary much at the higher frequencies used. The total decrease in capacity in going from 60 to 3000 cycles would be about 0.5 per cent. At 25 cycles a further change of 0.4 or 0.5 per cent would occur. Consequently the figures for the voltages at 3000 cycles deduced, as they are in the present paper, from values of the capacity obtained at 60 cycles are about 0.5 per cent low.

CORONA OBSERVATIONS, - RESULTS.

The plan of the work, as stated before, involved traversing the whole range of frequency in a period of time not greater than three hours. In this period it was possible to make one, or sometimes two, sets of observations at 60 cycles, a couple of sets in the neighborhood of 600 cycles, and fairly well placed sets from 1500 cycles up to the limit set by the rated speed of the machine or more often by the capacity of the direct current instrument. A set of observations consisted of from five to twelve observations of the corona voltage. It was always tried

to make a set of observations late in the period at some frequency the same as had been done earlier in the period. As a general thing these two sets agreed very closely, that is within a few tenths of 1 per cent, but sometimes the sets would differ by as much as 2 per cent. A record was kept of temperature and pressure although no particular use was made of it. The constancy of the corona voltage was not always such that full advantage could be taken of the available accuracy of the method. Sometimes the readings would repeat themselves very closely and then at other times the agreement would not be so good. The following table is an example of a set where the agreement was very good :

D.C.instr.	Low Tens. volt. of trans.	Speed in r.p.m.	D.C.Inst.	Low tens. volt. of trans.	Speed in r.p.m
140.2	102.3	968		102.1	969
140.5	102.3	968	139.5	101.5	
140.0	102.0	973	139.3	102.1	968
140.0	102.7	968	139.8		
140.0	102.1	968			
140.0	102.1				

The following table is an example of a rather bad set :

D.C.Instr.	Low tens. volt. of trans.	Speed in r.p.m.
89.0		1050
91.0	Off scale	1038
90.8		1038
91.0	i.e.over 130v.	1038
90.3		1038
90.9		1038
91.9		1037

The results for the tube 4.58 cm.in diamater are given in table I; those for the 6.35 cm.tube are given in table II. The voltages given were calculated by means of formula (2). These results are plotted in figures 5 and 6 respectively.

TABLE I.

CORONA VOLTAGES. DIAMETER OF TUBE 4.58 cm.

Diameter of wire	Series of observations	Frequency in cycles per second.	Voltage (max.)÷k.
0.317 cm. (0.1249 in.)	1	59.0	1.242
		1338	1.191
		1680	1.202
0.234 cm. (0.0924in.)	1	59.2	1.079
		558	1.061
		575	1.063
		1368	1.048
		1372	1.060
		1914	1.042
		1948	1.043
	2	58.5	1.081
		583	1.039
		1362	1.037
		1370	1.053
		1826	1.037
		1968	1.047
	3	58.0	1.076
		585	1.040
		1368	1.038
		1672	1.043
		1970	1.041
		2076	1.042
0.194 cm. (0.0763 in.)	1	59.5	0.998
		569	0.960
		2006	0.976
	2	58.8	0.999
		566	0.977
		567	0.973
		1336	0.986
		1884	0.982
	3	60.5	0.995
		590	0.950
		590	0.951
		1370	0.968
		1410	0.963
		1692	0.967
		2058	0.967
		2122	0.958

TABLE I (Continued)

Diameter of wire	Series of observations	Frequency in cycles per second	Voltage (max.) ÷ k.
0.164 cm. (0.0644 in.)	1	59.6	0.904
		568	0.877
		576	0.893
		1376	0.895
		1418	0.888
		1754	0.885
		2176	0.884
		2412	0.880
	2	58.9	0.919
		587	0.882
		1378	0.886
		1396	0.886
		1730	0.878
		2110	0.880
		2372	0.875
	3	58.3	0.928
		584	0.880
		1368	0.885
		1674	0.894
		2054	0.890
0.106 cm. (0.0418 in.)	1	59.5	0.758
		573	0.738
		575	0.738
		2640	0.737
		2650	0.739
		2822	0.728
	2	59.1	0.748
		598	0.728
		598	0.729
		1416	0.716
		2134	0.725
		2908	0.700
		2966	0.700
0.089 cm. (0.0350 in.)	1	59.5	0.689
		60.0	0.683
		558	0.686
		570	0.680
		2822	0.666
	2	59.4	0.683
		573	0.683
		1406	0.680
		2792	0.677

TABLE II.

CORONA VOLTAGE, DIAMETER OF TUBE 6.35 cm.

Diameter of wire.	Series of observations.	Frequency in cycles per second.	Voltage (max.). ÷ k.
0.317 cm. (0.1249 in.)	1	59.8	1.370
		578	1.313
		1294	1.338
		1622	1.313
	2	59.4	1.362
		274	1.402
		346	1.373
		423	1.361
		502	1.366
		566	1.360
		1298	1.350
		1440	1.350
		1638	1.336
0.234 cm. (0.0924 in.)	1	58.3	1.198
		585	1.147
		1360	1.148
		1684	1.161
	2	58.9	1.186
		284	1.223
		316	1.212
		354	1.191
		467	1.091
		529	1.166
		566	1.191
		570	1.181
		1098	1.166
		1460	1.170
		1848	1.151
	3	58.1	1.175
		58.6	1.191
		274	1.191
		342	1.197
		421	1.164
		469	1.122
		527	1.159
		570	1.174
		1392	1.174
0.164 cm. (0.0644 in.)	1	58.6	0.994
		585	0.955
		1372	0.961
		1740	0.952
		2102	0.959

TABLE II -(Continued).

Diameter of wire.	Series of observations	Frequency in cycles per second	Voltage (max.) ÷ k.
0.164 cm. (0.0644 in.)	2a (without inductance in low tension circuit)	272	1.031
		274	1.037
		347	1.031
		473	0.982
		528	1.016
		584	1.004
	2b (with ditto)	275	1.039
		346	1.019
		388	0.996
		423	0.982
		463	1.010
		528	1.011
		570	1.019
0.106 cm. (0.0418 in)	1	58.7	0.796
		59.4	0.795
		594	0.765
		1388	0.776
		1766	0.770
		2134	0.775
		2644	0.761

Corona voltages. Diameter of tube 4.58 cm.

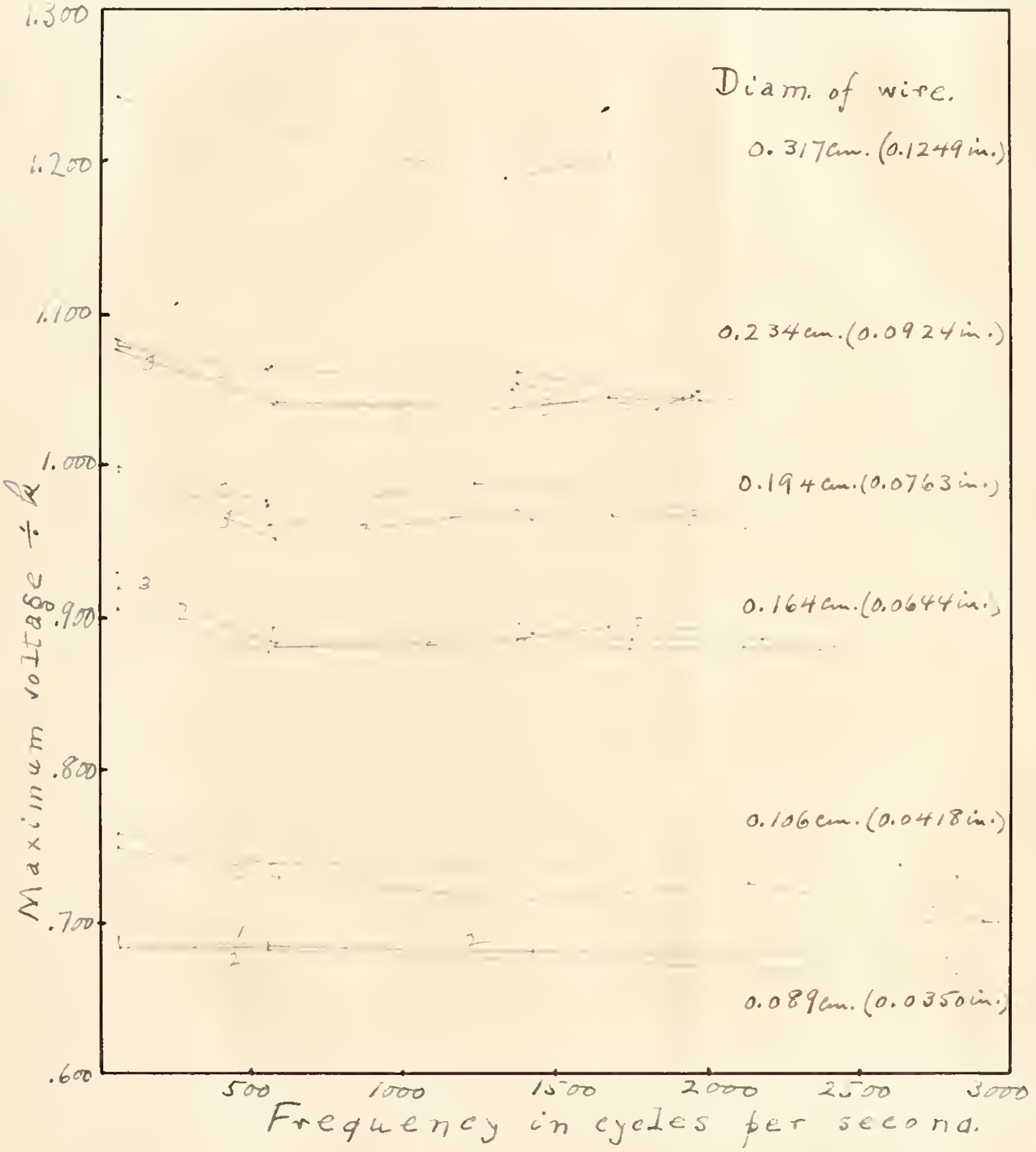

Fig. 5.

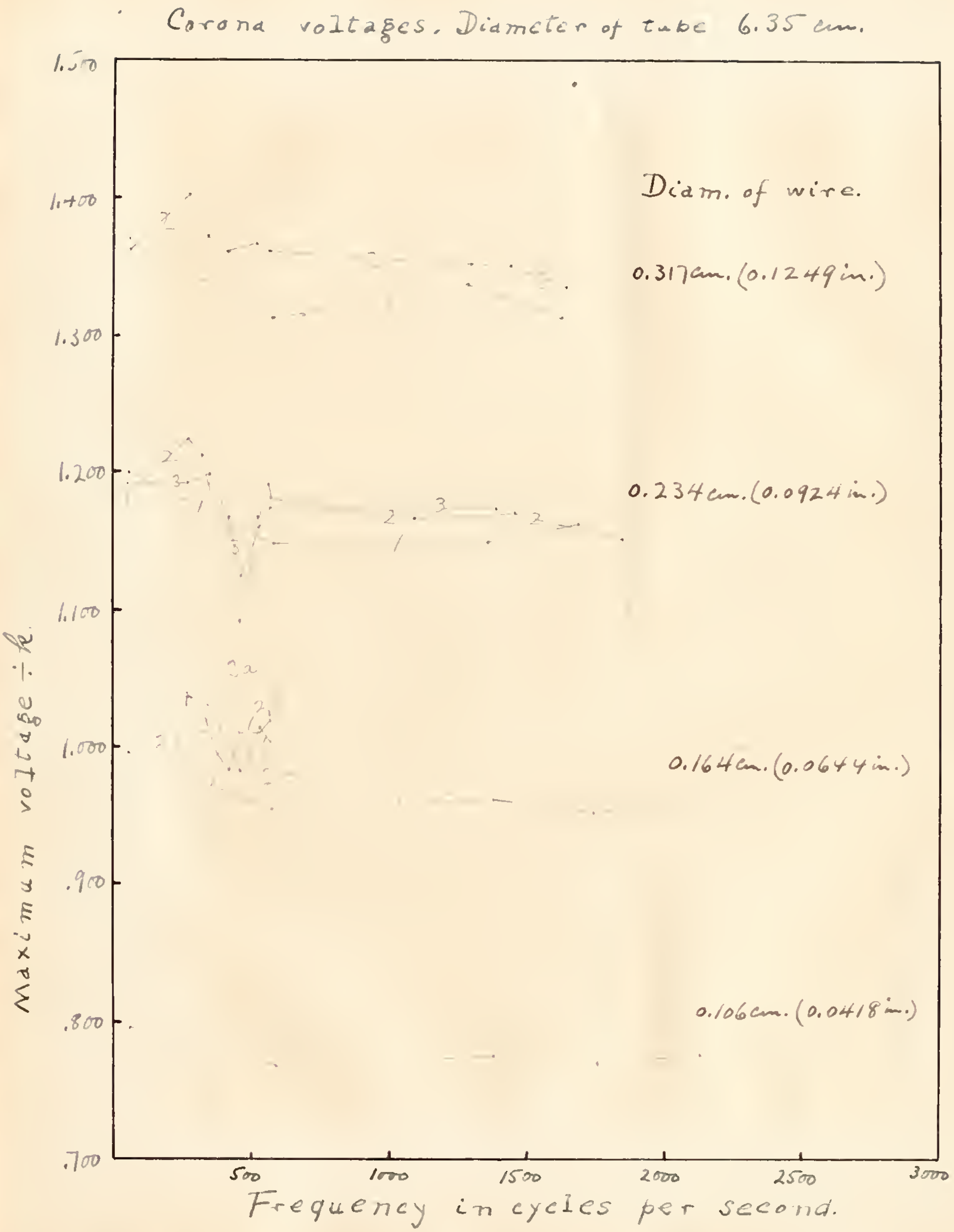
Corona voltages. Diameter of tube 6.35 cm.
Diam. of wire.
0.317 cm. (0.1249 in.)
0.234 cm. (0.0924 in.)
0.164 cm. (0.0644 in.)
0.106 cm. (0.0418 in.)
Maximum voltage ÷ k
1.500
1.400
1.300
1.200
1.100
1.000
.900
.800
.700
500
1000
1500
2000
2500
3000
Frequency in cycles per second.

Fig. 6.

In these figures the points of any one set are connected by straight lines in order to make interpretation easier.

The transformer connections used were as follows :From 1500 cycles upward the transformer was connected 125:1 because when connected 250:1 not enough voltage could be obtained to start the corona. From 270 cycles to 425 cycles the 125:1 connection was used because the 250:1 connection caused the corona tube to spark over even when the voltage was less than half the corona voltage. From 450 to 600 cycles the 250:1 connection was used because the 125:1 connection acted in the same way as the 250:1 connection did between 270 and 425 cycles. At 60 cycles the 125:1 connection was mostly used.

Looking at Fig.5 it can at once be seen that the corona is not as regular a phenomenon at higher frequencies as it is at 60 cycles. In the first place the points of any one set do not, as a rule, seem to lie on a regular curve and in the second place the figure, such as it is, which is formed by the points of a set can hardly be said to be of the same shape from day to day. These statements hold true more particularly of the larger sizes of wire. Moreover the temperature and pressure did not seem to have any discoverable effect on the shape or position of the curves. There seems however to be a decrease, amounting to 3 or 4 per cent, in the corona voltage in going from 60 to 2000 cycles this decrease being slightly more pronounced for the larger sizes. Fig. 6 shows a very remarkable state of affairs. In the case of the three largest sizes of wire assistance was available in making the readings. As a consequence it was possible to investigate the range of frequency from 300 to 600

cycles, which could not be done before for lack of time. The dip in the curves as well as the peak is very remarkable. In the largest size the peak is present but the dip has almost vanished. It is very significant that the points lying on the descent (for increasing frequency) were taken with a transformer ratio of 125:1, while the points on the ascent were taken with a ratio of 250:1. This suggests that possible the presence of the corona may not depend on the maximum value alone but may depend to some extent on the wave shape. Support is given to this idea by the results given in Table III. These show that the wave shapes obtained from the two different methods of connection differ consideraoly. The waves from the 125:1 connection are peaked while the ones from the 250:1 connection are flat-topped. Several very curious phenomena were noticed in this range of frequency. At about 420 or 425 cycles as the field current of the generator was being increased a point was reached when for the smallest possible change in the field current the reading of the d.c. instrument jumped from 35 to 80 with a corresponding change in the reading of the a.c. voltmeter; for further increase in the field current a moderate increase in the voltage occurred. This phenomenon may possibly be due to resonance of the higher harmonics of the voltage wave. Observations were taken at this frequency on the next to the largest size wire for values of the voltage above the unstable region; no unusual condition of the corona was noticed, but the voltage was rather subject to fluctuations. These fluctuations, however, were

not greater than one or two per cent. An attempt was made to avoid the instability of voltage mentioned above by placing a coil having considerable inductance (0.014 henry) in series with the transformer on the low tension side. The attempt was entirely successful, the readings of corona voltage being unusually steady but no effect of such treatment on the value of the corona voltage could be detected. [redacted]

It was mentioned above that at certain frequencies and with a certain connection of the transformer, the tube would spark over. One of such conditions seemed very remarkable. At 284 cycles the 250:1 ratio of the transformer was used. The voltage was steady and was gradually increased until it reached a value less than half of the corona voltage with the 125:1 connection. As soon as it reached this value the spark was heard in the tube and the voltage rose somewhat. This spark was not of the usual kind but was intermittent, occurring about once a second. No explanation of this phenomenon was evident.

An attempt was made to test directly the idea advanced above that the wave shape influenced the corona voltage. By connecting the armature of the two generators in series a wave with a very pronounced fifth harmonic could be secured. This was tried but no indubitable effect on the corona voltage could be detected. It is probable that it would take harmonics having a frequency far higher than 3000 cycles to produce any such effect.

It may be possible to account for the peculiar shape of

the curve taken in any one period by a variation in wave shape. The variation of the position of the curves from day to day, however, is even more puzzling as there seems to be no regular effect of temperature and pressure. Now each wire was carefully polished before being used ; consequently the surface of any wire was not precisely the same from one period of use to another period. It may be that at the high frequencies used the corona is more sensitive to the condition of the surface of the wire tha it is at commercial frequencies.

The corona from 1500 cycles upward seems to differ qualitatively as well as quantitatively from the corona at lower frequencies. At 60 cycles the gold-leaf in the electroscope would descend in a jerky fashion when the corona voltage was reached, the time taken for the electroscope to become wholly discharged being considerable, that is about 30 seconds or more. This jerkiness was more pronounced in the case of the smaller tube. In the case of this tube the jerkiness seemed to be inherent in the size of the tube. In the case of the larger tube it seemed possible that the jerkiness might be caused by the small fluctuations in the voltage which were not often absent. The cause of the jerkiness did not lie on the wire because it occurred no matter how carefully the wire was polished. From 300 to 600 cycles, when the corona voltage was reached the electroscope was discharged quickly but steadily,the time taken to discharge being one or two seconds. From 1500 to 3000 cycles the electroscope was discharged in a very small fraction of a second

the gold -leaf descending with great rapidity. No leak whatever was noticed before this rapid discharge occurred. Another interesting phenomenon noticed at these high frequencies was the vibration of the wire in the case of the open tube where the wire was supported at points some distance beyond the ends of the tube. At 1500 cycles the presence of the corona caused the wire to vibrate greatly. The vibration could not be noticed until the corona appeared. When the corona came the vibration was very noticeable. The vibration had no effect on the readings of the corona voltage because it did not occur until the corona had appeared. After the voltage had been lowered in order to take another reading the vibration stopped very quickly. Such a vibration, but at commercial frequencies, has been noticed before by other observers and the hypothesis has been advanced that it is due to a periodic variation in the voltage which happened to have the same frequency as the natural period of vibration of the wire. In the present case this explanation is not tenable because when the tension of the wire was altered greatly thus changing the natural period by a large amount the vibration persisted unchanged. It is thus seen that the vibration could not be caused by any periodic vibration in the voltage but probably owes its origin to some property of the corona itself. At 60 cycles the wire was perfectly steady even though the corona was extremely well marked.

Table III gives the values of effective high tension voltage,ratio of transformation,and peak factor,that is ratio of

TABLE III.

RATIO OF TRANSFORMATION AND PEAK FACTOR.

	Frequency in cycles per second.	Low tension voltage.	Ratio of transformation ÷ R	Peak factor ÷ P
	58.4	90.6	1.000	1.000
Trans. 250:1	594	40.1	2x1.148	0.869
	592	54.0	2x1.049	0.860
	1382	62.0	1.033	0.920
	1370	93.4	1.040	0.946
	1732	92.6	1.074	0.920
	2136	50.2	1.100	0.913
	2112	73.2	1.131	0.921
	2060	94.0	1.148	0.923
	2392	46.5	1.189	0.912
	2264	78.5	1.158	0.923
	2958	44.9	1.310	0.908
Trans 125:1	58.0	89.9	1.000	1.000
	274	115.5	1.007	1.120
	274	125.5	1.007	1.120
	350	101.5	1.012	1.028
	344	130.0	1.017	1.078
	417	130	1.017	1.028
	427	53.0	0.991	1.037
Trans. 250:1	471	37.1	2x1.027	0.907
	458	65.8	2x1.011	0.888
	526	32.5	2x1.052	0.881
	526	51.5	2x1.031	0.885
	522	75.5	2x1.014	0.889
	556	33.3	2x1.037	0.900
	560	46.9	2x1.021	0.896
	556	61.0	2x1.032	0.896
	558	74.5	2x1.038	0.894

R = ratio of transformation at 60 cycles == 125.1:1 or 250.2:1.

P = Peak factor at 60 cycles = 1.48 approx.

maximum to effective high tension voltage, for various voltages and frequencies throughout the whole range used. The peak factor at 60 cycles was about 1.48 ; the range of peak factors obtained in the course of the observations consequently is from 1.66 to 1.27. As the factor for a sine wave is 1.41, the wave shapes used do not differ, as far as the method can tell, very much from the sine shape. The ratio of transformation of the transformer was found not to change as much as did the ratio of the smaller transformer. From 60 to 2958 cycles the ratio increased 31 per cent.

The author has sought to account for the phenomena observed on the theory of the ionization of gases by collision but all the attempts thus far made have been unsuccessful. Several suggestions have been made as to possible ways in which the frequency might influence the corona. One of these is that there may be in the gas molecules electrons or systems of electrons which have natural periods of vibration comparable with the period of the impressed voltage;if the frequency of the impressed electric field were that of the natural vibration of the electrons in the molecule,resonance would occur and the electrons might be expelled from the molecule. It is highly improbable,however,that there are any systems in the molecule having a frequency of vibration such as can be attained by present experimental methods; the phenomena of the photoelectric effect indicate that the vibrating systems in the molecule capable of expelling electrons have frequencies not less [redacted]

than those of visible light waves. Another suggestion is that the corona would be influenced if the period of the impressed voltage were comparable with the time required for an electron to traverse its mean free path in the gas. In order for this last condition to be fulfilled, however, the frequency would have to be of the order of magnitude of millions of cycles per second. A third suggestion is that the corona is not an *instantaneous* phenomenon occurring as soon as the electric field strength reaches a certain amount but is a *cumulative* one depending upon the previous values of the field strength. This last suggestion has not been tested to any considerable extent, but seems to offer by far the greatest promise of the three. If this suggestion is correct and the corona actually depends upon the previous history of the voltage, it would seem probable that both frequency and wave shape have a decided effect upon the corona.

CONCLUSION.

In conclusion the author wishes to call attention again to the method employed in finding the maximum value of the voltage and to the results obtained on the variation of the ratio of transformation of the transformers with frequency. The facts elicited concerning the corona are as follows :

1. The corona voltage (maximum of the wave) in the range of frequencies from 300 to 3000 cycles per second is not subject to as simple and regular laws as it is at commercial frequencies.

2. The conditions influencing the corona within the

range mentioned are more numerous than at commercial frequencies.

3. The corona voltage at 2000 cycles is lower by 3 or 4 per cent than it is at 60 cycles.

4. The corona in the range of frequencies from 300 to 3000 cycles seems to differ qualitatively as well as quantitatively from the corona at 60 cycles.

The author wishes to acknowledge the valuable advice of Dr. A. H. Pfund concerning the mercury lamps and the helpful suggestions and assistance of Mr. M. W. Pullen throughout the course of the work.

BIOGRAPHICAL SKETCH.

William Stuart Gorton was born in Baltimore, Maryland, on March 28, 1889. He received his preparatory education in the public schools of Baltimore, graduating from the Baltimore City College in 1905. In the Fall of that year he entered The Johns Hopkins University, taking the Mathematical-Physical group of studies. He held a Hopkins Scholarship for three years and received the degree of Bachelor of Arts in 1908. In October of that year he entered the Graduate Department, taking as his subjects Physics, Applied Electricity and Mathematics. He held a University Scholarship during the year 1908-1909 and in the year 1909-1910 he was Student Assistant in the Physical Laboratory. He received the degree of Master of Arts in 1910 and was Fellow in Physics during 1910-1911. From 1911 to 1913 he was Instructor in Electrical Engineering at the Massachusetts Institute of Technology. During the year 1913-1914 he was Fellow by Courtesy at The Johns Hopkins University.